EMITTANCE PRESERVATION AT INJECTION INTO LHC

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Abstract

The very demanding LHC beam parameters put very strict requirements on the beam quality along the SPS-to-LHC transfer. In particular, the budget for the emittance increase is very tight. During the LHC commissioning, the emittances have been measured in the SPS, the two SPS-to-LHC transfer lines and in the LHC. Preliminary results show the importance of a very well controlled beam steering in the transfer lines together with the need of a robust trajectory correction strategy and transverse damping in order to guarantee long-term reproducibility. Another source comes from the tilt mismatch between the LHC and its transfer lines which generates coupling at injection into the LHC and in turn will contribute to emittance increase. Preliminary results are also discussed.

INTRODUCTION

The preservation of the transverse emittance from injection to collisions is crucial for the LHC luminosity performance. The transfer and injection process is particularly critical in this respect. The LHC is filled from the SPS via two transfer lines, each about 3 km long. For nominal performance the total emittance increase budget between SPS extraction and LHC collision energy is only $\varepsilon/\varepsilon_0 < 1.07$. This places stringent requirements on the various mismatch factors at injection. In total an emittance increase of 5 % should not be exceeded. The nominal emittance of nominal intensity bunches (1.15×10^{11} p^+ per bunch) is 3.5 μm: the allowed increase is therefore only about 0.08 μm.

SOURCES FOR EMITTANCE GROWTH

Beam stability, kicker ripple, betatron, dispersion and coupling mismatch at the LHC injection point all lead to emittance increase. How the different effects impact the emittance increase is summarised in [1]. For example, the emittance increase from steering errors at the injection point is given by

$$\frac{\varepsilon}{\varepsilon_0} = 1 + \frac{1}{2} \cdot \Delta e^2 \qquad (1)$$

with Δe being the steering error in betatron sigma. There is also a rotation angle between the reference frame of the transfer lines and the LHC. This 'tilt mismatch' leads to a phase dependant coupling, see [2], and emittance increase following

$$\frac{\varepsilon_x}{\varepsilon_{0x}} = 1 + \frac{1}{2} \cdot \left(\beta_x \gamma_y + \beta_y \gamma_x - 2\alpha_x \alpha_y - 2\right) \cdot \sin\theta^2 \qquad (2)$$

The emittance increase due to this effect is 1.3 % for TI 8 (tilt angle of 54 mrad) and 0.3 % (tilt angle of 20 mrad) and is presently uncorrectable, although correction schemes using skew quadrupoles are under study.

2010 OBSERVATIONS

Emittance Delivered to LHC

A series of BTV screens was used in the transfer lines for the emittance measurement. In the LHC wire scanners measured the beam sizes for circulating beam.

The optics in the line is very well under control, see Fig.1, after several years of measurements and corrections, see e.g. [4]. A big effort also went into understanding the dispersion matching into the LHC [4]. As a result, the transverse emittance is conserved (within the accuracy of the measurement) between SPS extraction and LHC injection – and this even for emittances below nominal. Table 1 shows the results for a comparative measurement done in beginning of July 2010 in the vertical plane.

Table 1: Vertical Emittance with Transverse Blow-up in the SPS, Measurement from 7th of July 2010

	ε_{yn} [μm]
SPS	3.3 ± 0.5
TI 2	3.2 ± 0.3
TI 8	3.4 ± 0.4
LHC B1	3 ± 0.3
LHC B2	3 ± 0.3

The emittance increase from SPS to LHC is clearly below the resolution of the measurement. The emittance measurement in the SPS and LHC is in fact a beam size measurement, using the nominal optics functions to estimate emittance – the estimate in the LHC could possibly be improved by using the measured (or interpolated) β function at the wirescanner, and by cross-checking with emittance measurement in the beam dump lines, each of which is equipped with three screens.

Fig. 2 shows the evolution of the emittance in the vertical plane for beam 1 during filling beginning of July.

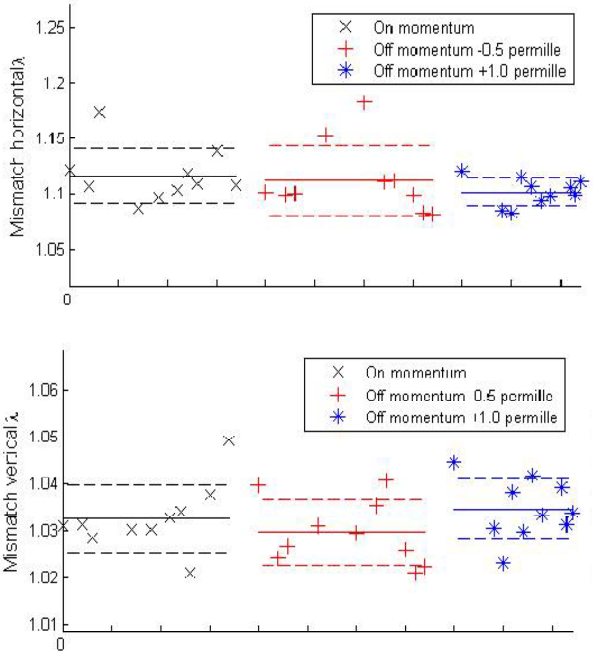

Figure 1: No measurable change of the betatron mismatch factor (to the nominal optics at the injection point) was measured for the transfer lines, also looking at possible momentum dependency. The betatron mismatch can be assumed to be in the order of 5 % for both lines. (The results in the horizontal plane show a larger mismatch due to using the nominal dispersion instead of the measured and not including the variation of the bunch length hence momentum spread). No measurable dependency on momentum has been observed. The LHC beta beating was found to be maximum 20 %, [3].

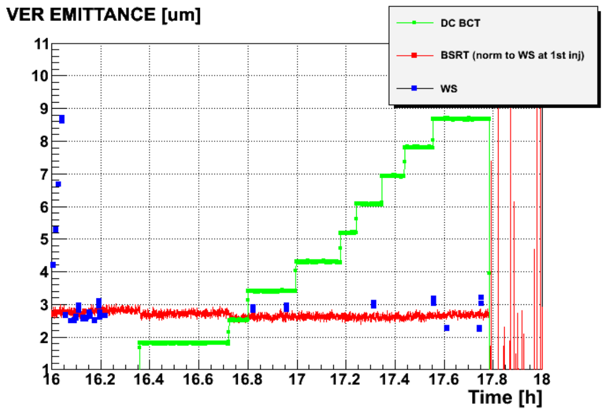

Figure 2. The evolution of the vertical emittance of beam 1 during filling (beam current curve in green) measured with wire scanner (blue) and synchrotron light monitor (red) on 7th of July. The emittance was around 3 μm.

Stability of Emittance from SPS

The emittance stability of single bunches of different intensities was measured during the commissioning campaign of injecting nominal LHC bunches in April 2010 using transverse blow-up. The screens in the transfer lines were used: no variation with intensity was seen, and the emittance was very stable, with an RMS of about 4% of the actual emittance (corresponding to 0.07 μm at 3.5 μm).

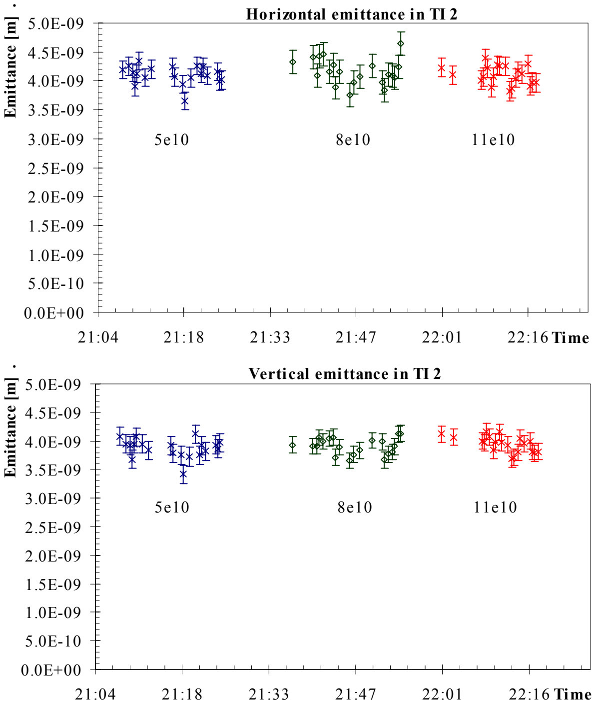

Figure 3. Emittances measured in TI 2 for different single bunch intensity. The geometric emittances are shown (4 nm corresponds to about 2 μm normalised emittance at 450 GeV).

Trajectory Stability

With the presently well controlled optics in the lines and LHC the largest contribution to emittance growth during the injection process comes from transfer line trajectory/LHC orbit changes and the associated injection oscillations.

Power converter instabilities lead from time to time to sudden appearances of oscillations down the lines. The power supplies of the SPS extraction septa seem to be particularly prone to these instabilities. Oscillations of amplitudes of ~ 1 σ have been observed with an oscillation phase compatible with the septa as source. The RMS of the trajectory excursions with respect to the reference, at the key locations of the TCDI collimators, is about 0.2 mm.

The injected trajectory can be well steered, with injection oscillations below about 0.5 mm, Fig. 4. However, in addition to the short-term random effects from power supplies, the trajectories in the lines are also slowly drifting. After four weeks without correction the trajectory had moved up to almost 700 μm at beam position monitors close to the injection point resulting in injection oscillations of about 1.5 mm compared to the initial value of < 0.5 mm. As a result, slight steering of the lines is needed every few weeks, essentially to centre the beam in the TCDI collimators and to correct the injection oscillations. The source of these drifts remains to be understood. No such drifts are observed with other beam lines close to the SPS-to-LHC lines, e.g. the CNGS beam line.

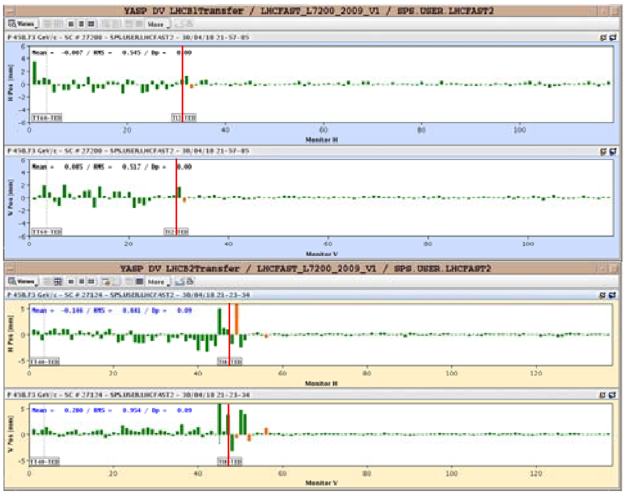

Figure 4. Injection oscillations at about 0.5 mm peak for both beams, both planes. The LHC arc is to the right of the vertical red line.

Losses on Transfer Line Collimators

The other issue is related to the transfer line collimators located at the end of the transfer lines.

Eventually 288 bunches per batch (1 x 10^{11} protons per bunch) will be injected into the LHC. This is a factor of about 20 above the estimated damage limit of equipment. Passive protection in addition to a complex interlocking system is needed at the end of the transfer lines to protect against large oscillations coming down the lines. There are three collimators per plane, with 60º phase advance per line. The required setting is 4.5 betatron σ [5]. Any changes of the trajectory at the transfer line collimators lead to losses at the collimators and hence to losses detected by the beam loss monitors on the close by LHC superconducting magnets.

Trajectory correction in the transfer line to improve injection oscillations therefore has to be done with care. Our current approach is hence not to correct at all up to the limit of injection oscillations with an amplitude of 1.5 mm. This limit has to be respected to preserve the minimum required LHC aperture for the present transfer line collimator setting (LHC minimum required aperture of 7.5 σ). The LHC transverse damper deals with these injection oscillations and guarantees emittance preservation.

TRANSVERSE DAMPING IN THE LHC

A powerful transverse feedback system ("Damper") has been installed in LHC covering a frequency range of 3 kHz to 20 MHz. It is designed to damp injection errors of up to 4 mm within less than 50 turns in order to prevent emittance increase due to a dilution of the dipolar injection error. The system has been described in detail elsewhere [6]. At large bunch spacing, as used in the run 2010 until mid September, bunches are fully treated individually, achieving similar damping times for all bunches within a batch. The system has been successfully commissioned in May 2010 and used since on the high intensity, nominal bunches for injection damping, during the ramp as well as with colliding beams. In order to improve the signal to noise ratio the maximum acceptance before saturation occurs has been reduced to 2 mm. This was possible due to the good stability of the injection process only requiring occasional steering to remain within the new set limit of +/- 2 mm.

The emittance increase at injection is given by

$$\frac{\varepsilon}{\varepsilon_0} = 1 + \frac{1}{2} \cdot \left(\frac{1}{1+\frac{\tau_{DC}}{\tau_d}} \right) \cdot \Delta e^2 \qquad (3)$$

where τ_{DC} is the decoherence time due to machine nonlinearities and τ_d is the active damping by the feedback system. It should be noted that in (3) a correction needs to be added in presence of an instability, effectively working against the feedback and increasing the overall damping time [6]. Moreover, (3) is only approximately correct as it lumps together all relevant decoherence phenomena and describes them with a single damping time implying an exponential decay. Numerical simulations can help to assess the situation and were used to predict the performance of the LHC damper [7]. In practice $\tau_d \ll \tau_{DC}$ is chosen to limit the emittance increase. During the design stage of the LHC damper 50 turns and 750 turns have been assumed, respectively, limiting the emittance increase to only 2.5 %. In practice the active damping time can be easily adjusted by a gain function in the damper system. The decoherence time may vary significantly with the machine state (chromaticty, octupoles etc.).

During the stable running period of August 2010 parameters of the damper system were not changed. Logging of damper signals became operational during this period, and injection oscillations were recorded with the available two pickups used by the feedback system per plane and beam. The pick-up signals were calibrated (in mm) using the orbit system as a reference. The transverse positions from the damper pick-ups of the first 8192 turns after injection, always for the first bunch of an injected batch, are recorded, for both beams and planes. Table 2 summarizes the optics functions at the pick-ups used by the feedback system, all located at quadrupoles Q7 and Q9 on the left or right side of point 4 of LHC where the beta functions are high for the plane under consideration.

Table 2: Optics Functions (v.6.503) at Damper Pick-ups

Pick-up	beam	plane	beta/m	Phase/degr.
BPMC.9L4.B1	1	H	127.2	reference
BPMC.7L4.B1	1	H	112.1	109.4
BPMC.9R4.B2	2	H	106.3	reference
BPMCA.7R4.B2	2	H	173.8	115.9
BPMCA.7R4.B1	1	V	126.7	reference
BPMCA.9R4.B1	1	V	137.8	62.2
BPMC.7L4.B2	2	V	169.5	reference
BPMC.9L4.B2	2	V	140.1	131.1

Using the signals from the two pick-ups the oscillation amplitude can be reconstructed by taking into account the phase advance ϕ between the two pick-ups

$$a = \sqrt{\frac{a_{Q7}^2 + a_{Q9}^2 - 2a_{Q7}a_{Q9}\cos\phi}{\sin^2\phi}} \tag{4}$$

where the amplitudes measured at pick-ups Q7 and Q9 have been first corrected for their different beta function (taking the theoretical optics model, and the observed beta-beat with respect to the ideal optics). With $a_{Q7,meas}$ and $a_{Q9,meas}$ as measured values the estimated values for a β=100 m are calculated as follows

$$\begin{aligned} a_{Q7} &= \frac{a_{Q7,meas}}{\sqrt{\beta_{Q7}/100\mathrm{m}}} \times \sqrt{c_{bb}} \\ a_{Q9} &= \frac{a_{Q9,meas}}{\sqrt{\beta_{Q9}/100\mathrm{m}}} \times \frac{1}{\sqrt{c_{bb}}} \end{aligned} \tag{5}$$

where the correction factor

$$c_{bb} = \frac{\max\left(|a_{Q9,meas}|/\sqrt{\beta_{Q9}/100\mathrm{m}}\right)}{\max\left(|a_{Q7,meas}|/\sqrt{\beta_{Q7}/100\mathrm{m}}\right)} \tag{6}$$

accounts for the beta beating observed from the injection oscillations in the very measurements. The mean beam position in the pick-up is removed before the analysis. Obviously there is an uncertainty, as one does not know the exact values of the beta functions. Eqn. (5) allocates the observed beating equally to both of the pick-ups used.

Figs 5 to 8 show as an example the analysed results for fill 1268 from August 9th, 2010. This fill had 25 bunches injected in seven batches with 1 to 4 bunches per batch, a typical fill during the early part of the stable running period in August 2010 before the number of bunches was doubled in late August.

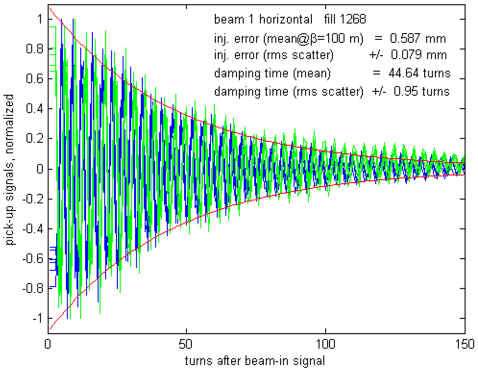

Figure 5: Horizontal injection oscillations of beam 1 for fill 1268, pick-ups Q7 (green) and Q9 (blue) as well as exponential fit from averages of the reconstructed data according to (4)

Recording starts at turn 4 (beam 1) and turn 5 (beam 2), after the beam-in signal due to a delay between the beam-in signal and the actual injection, and a synchronization pipeline delay in the damper low level system. The pick-up signals have been normalized to the maximum of the injection error observed on the respective pick-up with values of the mean damping time and injection error displayed in the figure. The scatter between the different injections is very low showing the good short term stability of the transfer line and the injection processes.

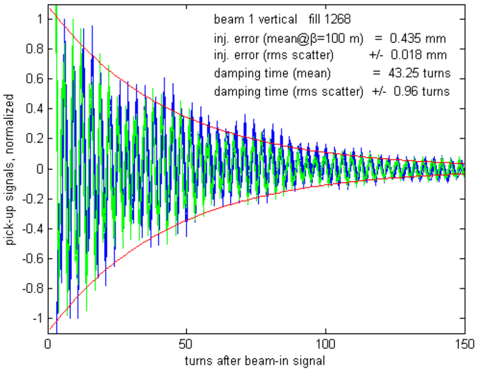

Figure 6: Vertical injection oscillations of beam 1 for fill 1268, pick-ups Q7 (green) and Q9 (blue) as well as exponential fit from averages of the reconstructed data according to (4)

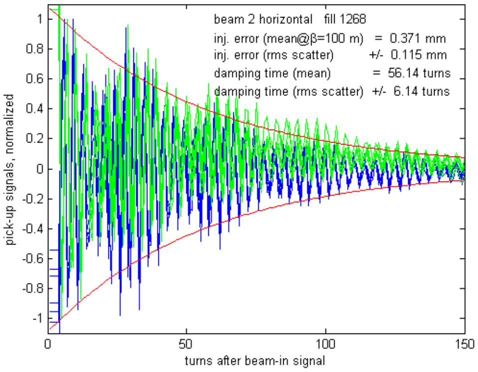

Figure 7: Horizontal injection oscillations of beam 2 for fill 1268, pick-ups Q7 (green) and Q9 (blue) as well as exponential fit from averages of the reconstructed data according to (4)

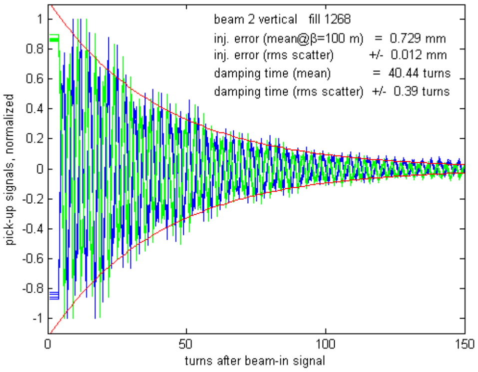

Figure 8: Vertical injection oscillations of beam 2 for fill 1268, pick-ups Q7 (green) and Q9 (blue) as well as

exponential fit from averages of the reconstructed data according to (4)

Injection Kicker Ripple

The injection kicker ripple was measured with beam, by recording the deflection of the beam as the timing of the kicker was varied, Fig. 9; initially the ripple was about a factor 2.5 above tolerance, but this was corrected with adjustments to the pulse forming network [8]. The emittance increase from the kicker ripple will become important as the number of injected bunches increases in the next phase of LHC operation; presently only 4 bunches have been injected at a time, and no effects on emittance increase from the kicker ripple have been seen, with the damper active.

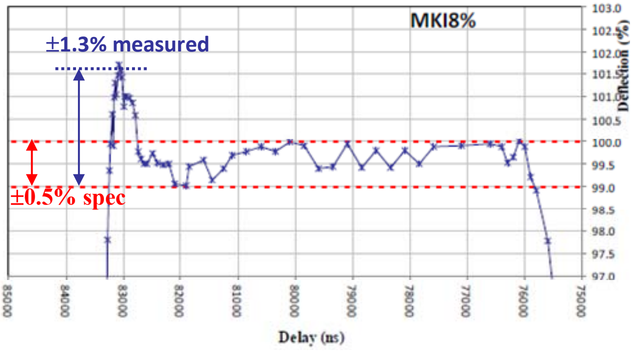

Figure 9: Measured ripple of the injection kicker for B2.

CONCLUSION AND OUTLOOK

The emittances are systematically measured in the SPS during the preparation of the LHC beams before injection and with circulating beam in the LHC at the injection plateau. It appears that the great care taken with the transfer line alignment, stability and optics has paid off, together with the excellent performance of the injection kickers and the transverse dampers, with the emittance dilution not measureable within the precision of the instruments available. Nominal emittance is achieved with ease; indeed for beam stability reasons in the LHC it is now necessary to blow the beam up transversely in the injectors, otherwise the emittances would be too small. For the future, when LHC luminosity optimisation will become extremely important, and when LHC may operate with smaller emittance, it will nevertheless be necessary to revisit the optical matching of the lines, and to maintain tight control over the injection process.

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